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A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation

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ABSTRACT

This paper presents an overview of the technical and economic aspects, as well as the market evolution of the Organic Rankine Cycle (ORC). This is an unconventional but very promising technology for the conversion of thermal energy, at low and medium temperatures, into electrical and/or mechanical energy on a small scale. As it makes a greater and/or more intensive use of its energy source, this technology could facilitate an electricity supply to unconnected areas, the self-production of energy, the desalination of seawater for human consumption, or even to increase the energy efficiency in the industrial sector respecting the environment. A look at the scientific publications on this topic shows an open research line, namely the selection of a suitable working fluid for these systems, since there is as yet none that provides all aspects that must be taken into account in ORCs. Furthermore, a description and an analysis of the applications of the proposed technology is carried out, specifying the main providers, which at the present time is limited mainly to the range 0.2–2 MWe with a cost of around 1 and 4×10^3 €/kWe. Lower powers are in pre-commercial status.

Contents

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1. Introduction

The implementation of public electric energy generating projects based on unconventional technologies that are, at the same time, environmentally sound, safe and which comply with occupational health criteria is, without doubt, fundamental in guaranteeing social equity and facilitating the execution of economic activities in the non interconnected zones (NIZ), where most territories are isolated, with a high degree of poverty and a lack of opportunities for socio-economic development. This is often caused by the lack of a suitable energy supply, despite being surrounded by abundant primary energy resources, such as solar radiation and biomass. What is more, the modern world is constantly demanding a greater energy supply. This challenge has to overcome, at the same time, such things as the high price of oil, climate change or the destruction of the ozone layer, as well as the economic crisis. These problems should encourage us to unite our efforts to develop new technologies that can convert such renewable energies as solar, wind or geothermal power [1–3] into electrical or/and mechanical energy [4]. In addition, the use of residual and/or low enthalpy heat rejected by industry, which makes up 50% or more of the heat generated in industry's installations, also need to be harnessed. However, as conventional steam power cycles cannot give a better performance to recover low grade waste heat, it is necessary to analyze other types of processes, such as the organic Rankine cycle (ORC), whose most important feature is the possibility of using different low temperature heat sources for power generation, as has been proposed by [1–6], amongst many other authors.

In this sense, the ORC is emerging as a promising process for the conversion of these low and medium temperature heats, from renewable energies and from industry, into electricity [7–11]. In the recent years, commercial applications of this technology, with power ranges of 0.2–2 MWe, have soared worldwide. ORMAT, in the United States and Turboden, in Europe, are the most representative companies that have developed plants, mainly for the use of geothermal and biomass energy, respectively. However, the lower power modules are still at the prototype stage, due to the lack of suitable equipment (mainly the turbine) and the difficulty in finding the most suitable working fluid. This has a great influence on the design of each process [8], because, depending on the application, the source and the heat level to be used, the fluid must have optimum thermodynamic properties at lower temperatures and pressures and must satisfy multiple criteria, such as being economical, nontoxic, nonflamable, environmentally friendly, as well as allowing a high use of the energy availability of the heat source, etc. Thus, the aim of this paper is to present a description and analysis of the uses of this technology, from both a technological and an economic point of view.

2. Operation principle

The ORC operation principle is the same as the conventional Rankine cycle, but in this case, the working fluid is an organic compound of low boiling point instead of water, thus decreasing the temperature needed for evaporation. A pump pressurizes the liquid fluid, which is injected into an evaporator (heat source) to produce a vapor that is expanded in a turbine connected to a generator. Finally, the output vapor is condensed and sucked up by the pump to start the new cycle (Fig. 1I). An Internal Heat Exchanger (IHX) can also be included to make even better use of the energy from the expanded vapor, preheating the pump fluid that will enter the evaporator as shown in Fig. 1II.

According to the state points shown in the schematic diagram of the simple process in Fig. 1I, Fig. 2 presents the power cycle in a *T*–*s*-diagram plotted with [12] data. As an example, an ideal cycle process is shown by segments, which are built from the state points 1, 2_{is}, 3 and 4_{is} marked with (◯). The line segment 1–2_{is} represents an isentropic expansion with a production of output work. Heat is extracted from 2_{is} to 3 along a constant subcritical pressure line. Then, an ideal compression of the saturated liquid from pressure at state point 3 to state point 4_{is}. Finally, the segment 4_{is}–1 represents the heat addition at constant subcritical pressure to the highest temperature of the cycle at state point 1.

The previous case, but operating under conditions in which the expansion process as well as compression process have a certain efficiency, i.e., a more realistic cycle, is represented by the segments built from the state points 1, 2, 3 and 4 marked with (◯) in the same Fig. 2, which are also related to Fig. 1I. In order to increase the process efficiency, an IHX is introduced, as can be seen in Fig. 1II, in which a portion of the rejected heat, represented by an enthalpy drop from 2 to 2_{IHX} at constant subcritical pressure, is transferred back to the fluid, raising its enthalpy from 4 to 4_{IHX} at constant subcritical pressure. Net heat rejection is indicated by the enthalpy drop from 2_{IHX} to 3 at constant subcritical pressure. State point 3 is at the lowest temperature of the cycle and above the temperature of the heat sink. Net input heat to the cycle occurs from 4 (or 4_{IHX}) to 1 at constant pressure. Net work output is the difference between the output work from state points 1 to 2 and the input work pump from state points 3 to 4.

3. Selection of the working fluid

The selection of the working fluid for its use in ORC cycles is a crucial aspect because, depending on the application, the source and the level of heat to be used, the fluid must have optimum thermodynamic properties at the lowest possible temperatures and pressures and also satisfy several criteria, such as being economical, nontoxic, nonflammable, environmentally friendly, allowing a high use of the available energy from the heat source, etc. This limits the list to just a few fluids if all aspects that can restrict their use are considered, such as:

- *Environmental:* Some fluids are or are being restricted by international agreement [13] depending on their Ozone Depleting Potential (ODP) defined and limited in the Montreal Protocol, or on the Greenhouse Warming Potential (GWP) in relation with the limitations in the Kyoto Protocol, which intend to prevent the destruction of the ozone layer and emission of gases causing the greenhouse effect, respectively.
- *Safety*: The fluid must be non-toxic (in case of leaks at the plant or during handling), non-corrosive (evidently avoiding higher maintenance costs and/or damage to the facilities) and non-flammable. Thus, the security classification of the ASHRAE is used as an indicator of the fluids' degree of danger.

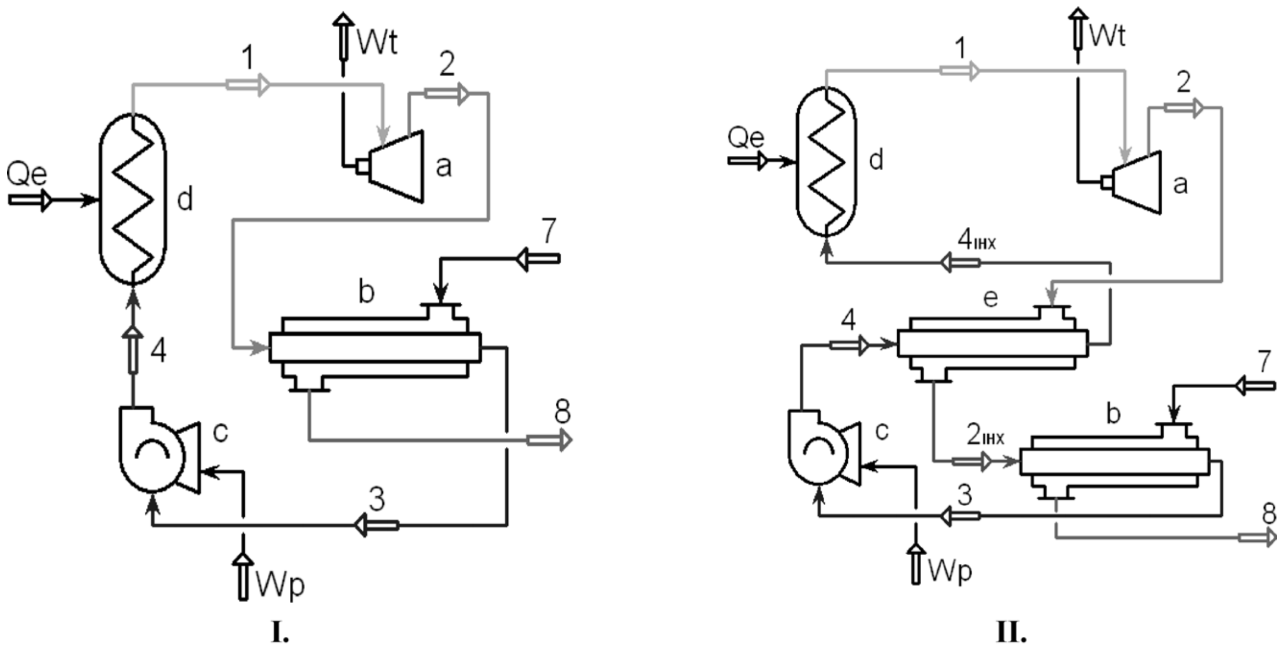


Fig. 1. Schematic diagram of the simple process (I) and with IHX (II). (a) Turbine, (b) condenser, (c) pump, (d) evaporator, (e) internal heat exchanger.

- *Stability*: The chemical stability of the fluid used can limit the temperature of the heat source, because it can be broken down when exposed to certain temperatures, producing substances that could modify the way in which the cycle works. In addition, it may result in toxic and irritating compounds that could induce health problems if leaks occur.
- *Pressure:* When a fluid requires high pressures to make the process efficient, the equipment costs are higher due to the high resistance they must endure, also increasing the complexity of the plant.
- *Availability and low cost:* A fluid of low availability and/or high cost limits its use in ORC plants for obvious reasons, in view of the financial viability of projects.
- *Latent heat and molecular weight:* The greater the molecular weight and latent heat of the fluid, the more energy can be absorbed from the heat source in the evaporator and, therefore, the size of the installation and the comsuption of the pump can be smaller, due to the decrease in the flow rate required.
- *Low freezing point:* The freezing point of the fluid must be lower than the lowest temperature of the cycle.
- *Curve of saturation*: The thermodynamic properties of the fluid mean that the slope of the saturation curve will be negative, vertical or positive, which will greatly affect the design and efficiency of the ORC. Fig. 3a–c shows a schematic diagram Temperature–Entropy (*T*–*s*) for fluids with a negative (a), vertical (b) and positive (c) saturation curve, called wet, isentropic and dry, respectively. Since the objective of the ORC focuses on the use of heat at low and medium temperatures, the overheating of the vapor, as in the traditional steam Rankine cycle, is not appropriate. Furthermore, as shown in Fig. 3a, when an expansion of a wet fluid without overheating happens (represented by state point segment 1–2), it falls in the liquid/vapor area, causing damage to the turbine and inefficiencies in the cycle, among other reasons, because of the phase change. The opposite case occurs with the isentropic and dry fluids which, without any type of overheating, expand and fall in the saturated vapor zone (Fig. 3b) and/or in the superheated zone (Fig. 3c) respectively. Therefore, in this last case, an intermediate interchange may be needed that allows even more of the energy of the expanded vapor to be used, preheating the fluid from the pump that enters the evaporator, thereby increasing the efficiency of the cycle.

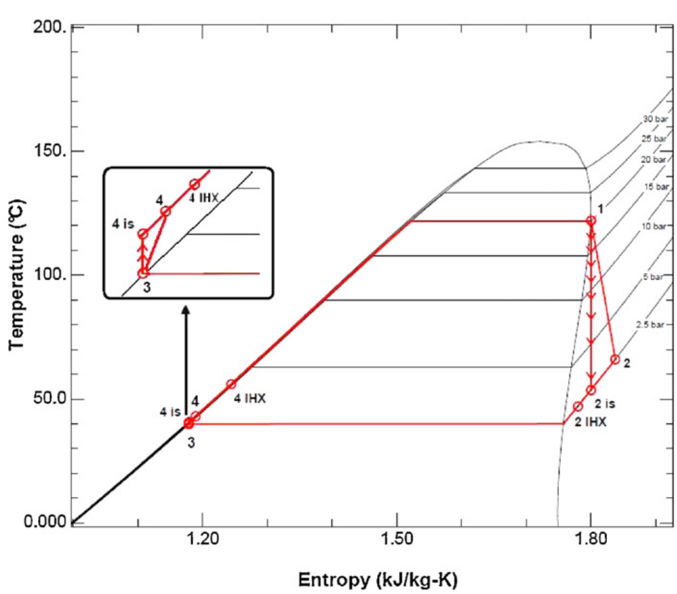
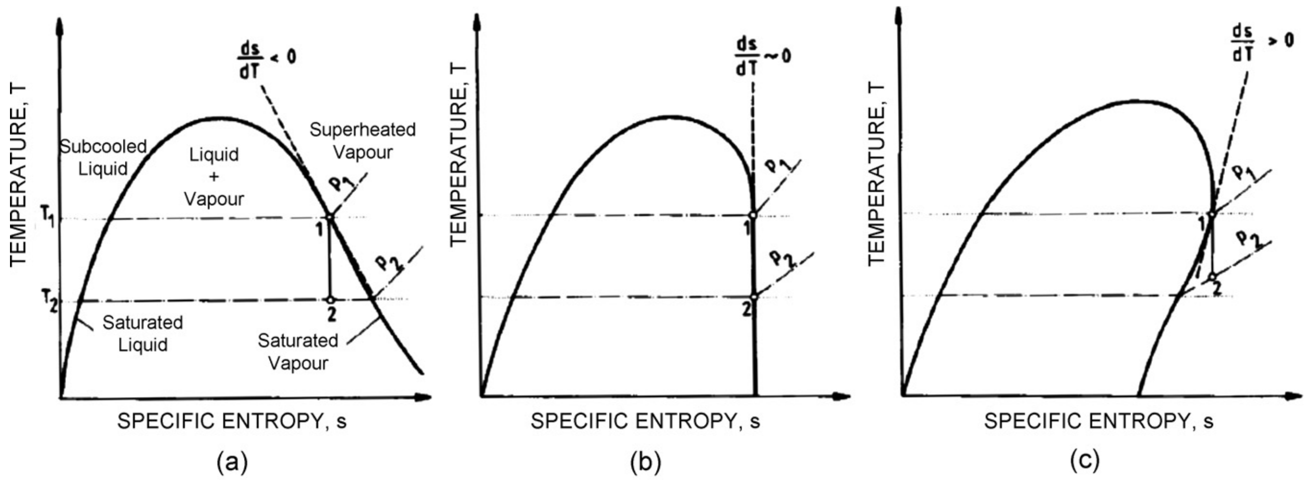


Fig. 2. Typical *T*–*s* diagram for the Rankine power cycle.

The low temperatures that are intended for use with the ORC make the overall efficiency of the cycle was highly sensitive to inefficiencies in heat transfer, which depends heavily on the thermodynamic properties of the fluid and the conditions under which it is operating. Therefore, there are numerous studies that lead to finding a suitable working fluid for these systems and to satisfying, as far as possible, all aspects mentioned at the beginning of this section. In 1985, in [5], a study of 68 potential working fluids was performed, of which only three gave the best results (R11, R113 and R114). These are fluids not recommended nowadays due to the global policies of environmental conservation [13]. In [4], the efficiency of the ORC was analyzed using benzene, ammonia, R134a,



source [5]

Fig. 3. Diagram *T–s* for fluids (a) wet, (b) isentropic and (c) dry.

R113, R11 and R12, obtaining greater efficiencies for the last two. However, they are substances of limited use [13]. Thus, a revision of the available literature about low/medium temperature Rankine cycles has allowed the analysis of more than 100 working fluids for use in ORC systems. In [6], a thermodynamic screening of 31 pure components (alkanes, fluorinated alkanes, ethers and fluorinated ethers) is shown for an ORC that operates at a maximum of 100 °C and whose heat source comes from a geothermal source with a slightly higher temperature. Another study that compares (from a thermodynamic, environmental and safety point of view) the use of 20 fluids operating at a temperature even lower than the previous (75 °C), in a solar organic Rankine cycle system, has been done by [8]. In [7], the authors base the study on a cycle with maximum temperatures between 250 and 350 °C, finding the highest efficiencies with the family of alkylbenzenes. A screening of 35 working fluids, considering the influence that their thermodynamic and physical properties (latent heat, density and specific heat), stability, environmental impacts, safety, compatibility, availability and cost have on the conversion of low temperature heats into electricity, is carried out in [14]. It shows that these properties of the working fluids play a vital role in the cycle performance. Other researchers who have analyzed the characteristics and behavior of different fluids for their use in ORC systems are, among others, [9,10] and [15,16], from which it can be inferred that R245fa and R134a are good candidates for processes whose heat source is at low temperatures.

From this Section 3, it can be seen that the selection of the working fluids for use in ORC cycles is a crucial aspect, being their classification dependent on the temperature of the heat source, grouped by type and/or class, as shown in Fig. 4. Obviously, it is clear that this source of heat determines the use of one or another type of fluid, as these are limited to a range of temperatures defined by their own properties and/or thermophysical properties, such as temperature and critical pressure, chemical stability, security, etc.

4. Applications of the ORC technology according to the energy source

The modularity and versatility of the ORC technology, as well as the possibility of using it at different temperature ranges, allows the repowering of plants currently in use, that is, the coupling of processes, for example, to use the residual thermal energy and produce electricity by acting as a bottoming cycle, or as a topping cycle, to generate electrical energy and use the residual heat remaining from this process, i.e., acting as a Combined Heat and Power plant (CHP). Fig. 5 clearly shows most of the configurations that can be done with the ORC. It shows how, depending on the source, the energy from the heat generated (using primary sources of energy such as solar, geothermal or biomass combustion) and/or recovered from different sources (such as the waste heat of processes) and/or from other technologies (such as other power cycles), allows the generation of electricity and, depending on the temperature of the heat source as well as the heat sink, to extract heat through the process of condensation to produce cold (with an absorption machine) and/or heating/drying, or even more power (cycles in cascade). In Fig. 5, the green line indicates electrical energy, while the orange and red lines indicate the flow of heat transfer fluid.

An ample review of the scientific literature on ORC that deals with the technical and/or economic aspects of the use, transformation or exploitation processes of energy, which follow the possible configurations compiled in Fig. 5, is now discussed in detail:

4.1. Solar power applications

In recent years, several technologies different from the photovoltaic have been developed to transform solar radiation into mechanical energy and/or electricity by means of a generator. One such technology is the ORC as it is described in the next two next sections.

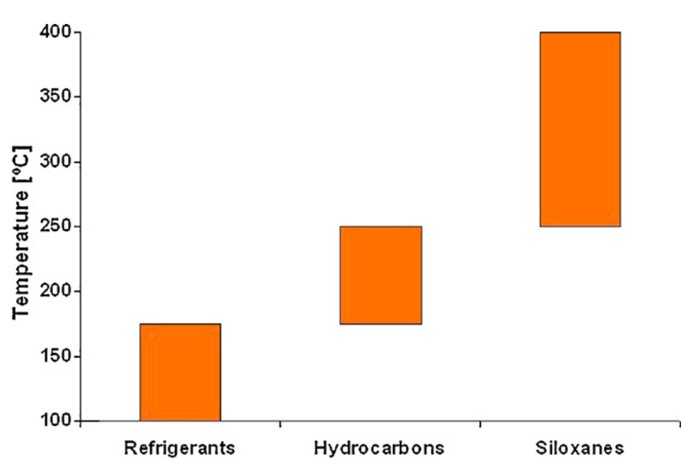


Fig. 4. Typical classification of working fluids in ORC systems, according to the level of temperature of the heat source.

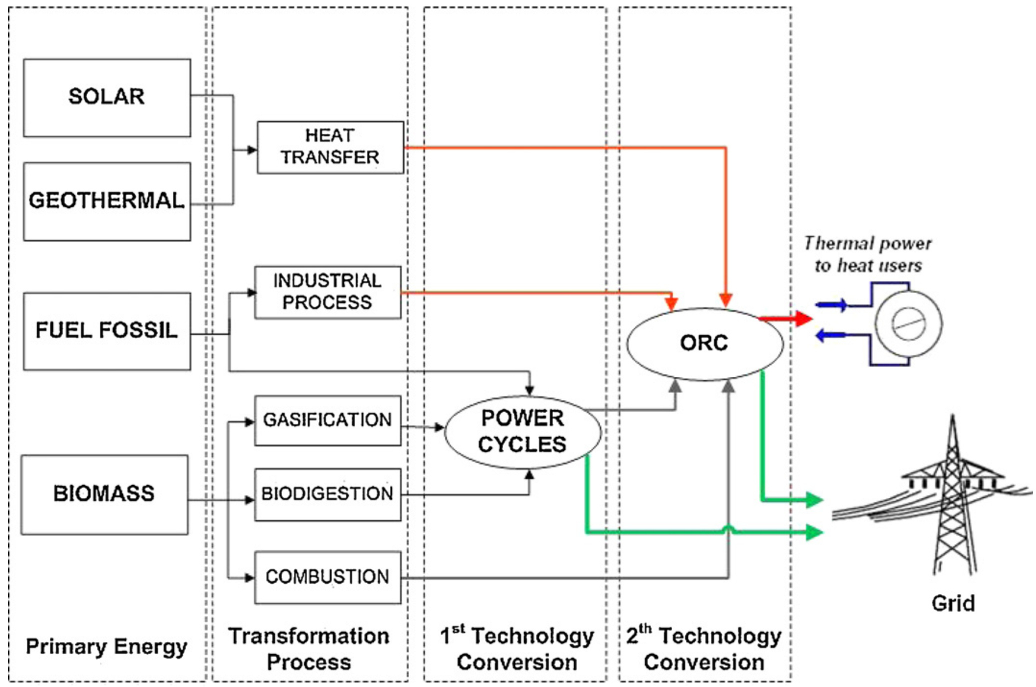


Fig. 5. Diagram of possible applications of ORC according to the energy source. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

4.1.1. *Thermoelectric plants*

Parabolic discs using Stirling engines are an example of small power generation with solar energy, whereas on a large scale, tower solar fields and Parabolic Trough Collectors (PTC) are processes whose operating principle is similar: the sun's rays are reflected in mirrors in order to concentrate the energy and then heat a fluid, be it through a heat transfer fluid (which requires less pressure in the solar field, but increases the heat losses in the transfer to the steam cycle), or directly to the working fluid (whose technology is emerging due to the problems of the two-phase flow in terms of strength and cost of required materials [17]). However, these are steam cycles that require high temperatures, high pressures, and therefore need a high installed capacity of about 30–80 MWe to be profitable (typical solar steam systems are 50 MWe covering 2 km^2, compared with 0.01 km^2 required for a 1 MWe ORC [18]). This opens up the way to installing ORCs, where solar radiation can directly heat the organic working fluid (at relatively low operating pressures) or the heat transfer fluid and, in this way, store heat during the day to continue operating the plant during the night, as presented schematically in Fig. 6.

Nowadays, there are very few ORC plants working with solar energy. However, there is a plant of 1 MWe in the USA [19] that combines PTC with ORC supplied by the company ORMAT [20], which uses n-pentane as the working fluid and whose investment was 5730 €/kWe, giving a cost of 17 c€/kWh and a solar efficiency to electricity of 8.4% [19]. Theoretically, among others [21–23], have conducted studies on this type of facilities that report efficiencies from 5.0% to 20.0% (which of course depends on the type of fluid and collectors used, in addition to other aspects). However, since one of the major impediments to implementing such small-scale plants is the captation system [24], at present, other concentrator technologies are being developed, such as the Fresnel type, which supposes a lower investment and maintenance than PTC, thus making this type of small power plants viable. Similarly, it is worth noting that some researchers have experimentally evaluated ORC cycles with low and medium temperature collecting panels, generally used for the production of domestic hot water and heating, yielding acceptable results in terms of efficiency (between 4.2% and 5.6%) and technical feasibility [25]. On a theoretical level, to cite some research, such as [22–24] and [26,27], efficiencies of between approximately 6.4% and 16% can be obtained with this type of collectors.

4.1.2. *Water desalination*

The ORC, instead of generating electricity, can be coupled directly to drive the pump of a process like reverse osmosis (RO) as is presented schematically in Fig. 7. Thus, fresh water can be produced autonomously in dry areas, where it is scarce, using only sunlight as the energy source, something that is abundant in these same locations. These systems have been analyzed theoretically with other desalination processes, for example [22], compared ORC-RO with different types of solar collectors and whose economic performance ranged from 2 to 3.3 €/m^3 for brackish water and from 4.3 to 9.5 €/m^3 for seawater, with the lowest values

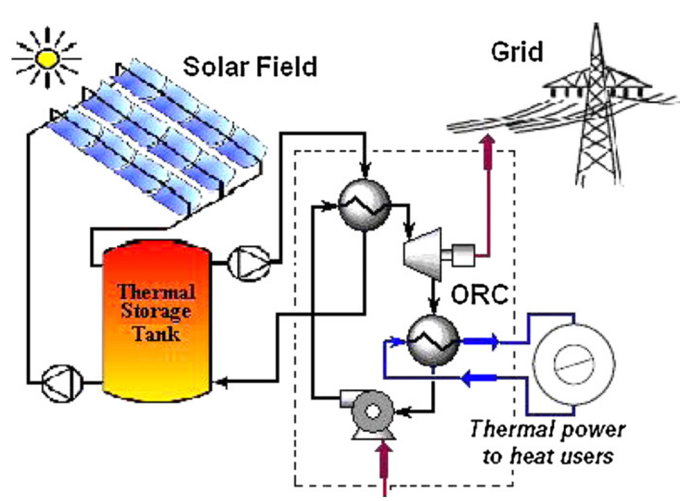


Fig. 6. Schematic diagram of an ORC connected with a small solar field and with energy storage.

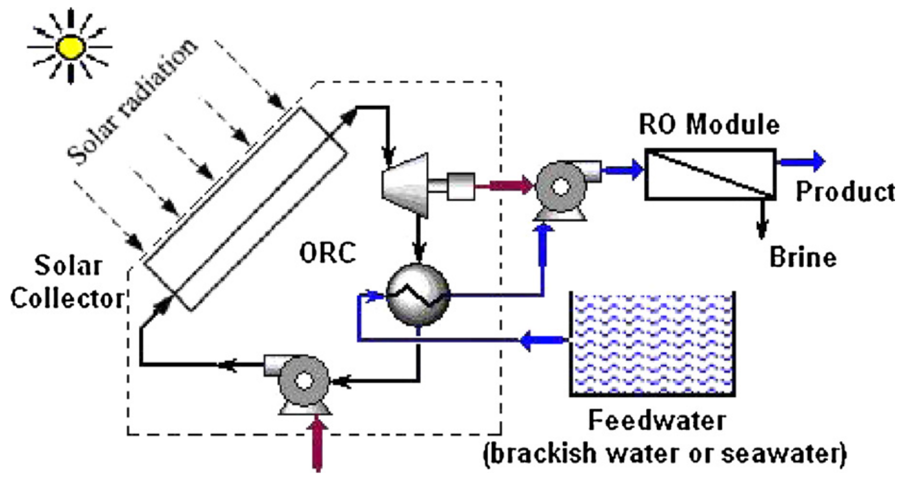


Fig. 7. ORC with solar energy and coupled directly to an RO process.

for PTC and the highest for Flat Plate Collectors (FTC); whereas, for the RO-photovoltaic system, the specific cost is from 3.8 to 4.3 €/m^3 and from 12.8 to 14.8 €/m^3 for brackish and seawater respectively. Similarly, in [28], different types and trademarks of solar collectors (AoSol 1.12X, FPC Vitosol 200F, FPC SchücoSol U.5 DG and ETC Vitosol 300) are compared for a low-temperature ORC coupled to an RO process and whose volumetric flow rate of desalted water, produced per square meter of aperture area, for seawater/brackish water, was 29.7/102.2, 32.8/112.5, 37.8/129.5 and 50.8/174.3 L/(hm^2) heating the working fluid (R245fa) directly; and 21.8/75.3, 24.1/82.5, 29.3/100.7 and 42.8/147.2 L/(hm^2) in the case of indirect heating with CPC AoSol 1.12X, FPC Vitosol 200F, FPC SchücoSol U.5 DG and ETC Vitosol 300, respectively [21] compares the efficiency obtained with different PTC and working fluids, showing that it is possible, with the PTC, trademark LS3, to achieve overall efficiencies between 20.6% and 14% with toluene, 18.3% and 11.9% with octamethylcyclotetrasiloxane (D4) and 17% and 10% with hexamethyldisiloxane (MM). These values are between 16% and 9% for toluene, 14.5% and 7.4% for D4 and 14.4% and 7.8% for MM if the PTC trademark IND300 is used [29] shows how the desalination process, coupled to an ORC, exhibits a lower specific consumption of solar energy than solar distillation and solar photovoltaic RO systems. These same authors in [30], and others in [31], discuss the addition of a second ORC powered by the thermal power rejected by the top ORC, forming a double cascade ORC. This provides the power consumption of the auxiliary equipment system ORC-OR, showing, for the case of [30], productions of desalinated water directly heating the toluene (working fluid of top cycle, while the bottom cycle consists of the isopentane) of 76.7 and 56.7 L/(hm^2) for LS3 and IND300 PTC respectively. If the heating is done indirectly with another fluid, it would obtain 75 and 45 L/(hm^2), respectively. With the same configuration as the previous research, but with R45fa as the working fluid of the top cycle, and R134a for the bottom cycle [31], calculated the specific fresh water cost at about 6 €/m^3 for the cases with 40° of slope collectors, and of 360, 420 and 480 m^2 of gross area collectors, obtaining generally recognized results in PV-RO systems. At the experimental level, the Powersol project [32] aims to develop a solar thermal-driven mechanical power generation based on a solar-heated thermodynamic cycle, optimized by means of experimental testing with selected working fluids and three solar collector prototypes for electricity generation and desalination by reverse osmosis. Other publications on these systems with experimental basis are reported in [33,34], whose results allow us to conclude (as with the theory presented in [29]) that the ORC-RO has a lower specific energy consumption, as compared with the solar distillation process and the photovoltaic system RO. Although the cost of water produced of 12.53 €/m^3 is interesting, further research is needed to make greater advances in this technology.

4.2. Biomass applications

The two main reasons for the use of biomass in situ in facilities of combined heat and power are its low energy density, which increases the transport costs, and the demand for electricity and heat or cold (by means of absorption equipment), which are often located in the same site. Power production from biomass can occur through external combustion (e.g., steam cycles, organic Rankine cycles, Stirling engines), or internal combustion after gasification or pyrolysis (e.g., gas engines, IGCC). External combustion has the disadvantage of delivering limited conversion efficiencies (30–35% max.), whereas internal combustion is characterized by the potential of high efficiencies, but it always needs a severe and mostly problematic gas cleaning [35]. In the next three sections, how the ORC is of great interest for power production from biomass combustion in both external and internal combustion engines will be explained in more detail.

4.2.1. Biomass combustion

In 2008, there were 97 recognized facilities with ORC systems using a biomass boiler as the source of heat. This supposes 47% of the worldwide use of the ORC in terms of quantity, but only 5.8% of the market in terms of power. The total installed capacity of these sites is 88 MWe [36]. However, with the growing interest in this technology over recent years, there are more than 140 medium scale facilities (0.2–2 MWe) for electrical energy generation from biomass combustion with ORC technology (e.g., Allendorf Eder Germany 200 kWe, Arta Terme Italy 500 kWe, Bregenz, Austria 1000 kWe, to mention just a few [18]), in which the residual heat of the condensation is additionally used for residential purposes such as heating and domestic hot water; as well as for drying and/or cooling in industrial processes, as shown in Fig. 8. The lack of conventional steam cycles in this type of project is due to the high pressures and temperatures required for optimal performance with this technology, which increases the maintenance costs and staff, which means that installations need more than 5 MWe to be economically viable. On the other hand, the ORC technology offers the possibility of co-generating on a small-scale, as well as other advantages such as low maintenance and staffing costs [10], no high pressure, automatic and continuous working, removal of corrosion

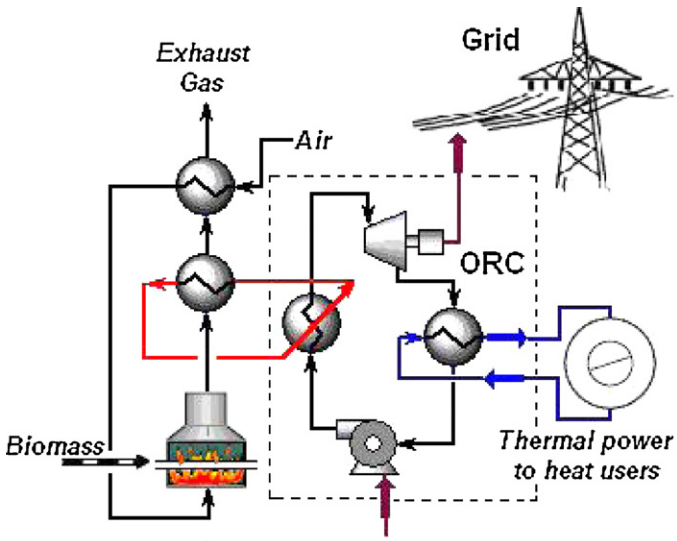


Fig. 8. Cogeneration with ORC technology and biomass combustion.

problems by not using water, easy starting-up, reliability and high efficiency even at partial load [2]. All this puts the relatively low electrical efficiency of these systems on a secondary level.

The selection of the working fluid in ORC technology systems with biomass combustion has the peculiarity of working with relatively high temperature levels. The temperature of the condenser can be between 60 and 120 °C [18] to satisfy the needs of heat users. This means that many fluids cannot be used because their vapor pressure is quite high, even at condensation temperature. The turbine inlet temperature could be close to flame temperature, but organic fluids would become chemically unstable. Therefore, the maximum process temperature is limited to about 330 °C [7].

Normally, the heat of the gases from the combustion of biomass is transferred to the working fluid through a secondary fluid (as in Fig. 8), a thermal oil that prevents overheating and allows the heat exchange of exhaust gas at atmospheric pressure, thus achieving greater process control.

The cost for a commercial ORC module of 1 MWe used for biomass applications is currently about 1600 €/kWe [22], while [37] shows how the ORC cogeneration units are viable for typical conditions in the European Union; in which case, the value of electricity required must be around 10 c€/kWh for power plants larger than 1.5 MWe, while for 1 MWe plants, the value of electricity must be at least 14 c€/kWh. On an industrial scale, in [38], heat pellet production plants are compared with the CHP solution based on a biomass combustion system, an ORC unit and a belt dryer fed by hot water coming from the ORC condenser. That work shows how CHP plants for productive purposes can be economically competitive with a value of electricity over 16 c€/kWh for plants with a pellet production capacity of 4 t/h, while above 8 t/h, the value of electricity must be between 10 and 12 c€/kWh.

Regarding micro-scale CHP facilities, which would be particularly useful in the residential sector, in [39], a small scale biomass powered ORC of 10 kWe was designed, built and tested to produce heat and power and to demonstrate its full operability and/or technical feasibility. However, it can be said that they are not yet economically viable, due to the initial investment cost and a long payback period. In spite of this, even when it is evident that the savings that this type of technology supposes for primary energy consumption and the reduction of CO_2 emissions; further research is needed in the development of low-cost micro-scale CHP systems with innovative technologies [40].

4.2.2. Gasification

When comparing ORC and gasification technologies for biomass CHP plants in economic and technical terms, as presented in [41], it is shown that gasification gives a higher yield, but the initial

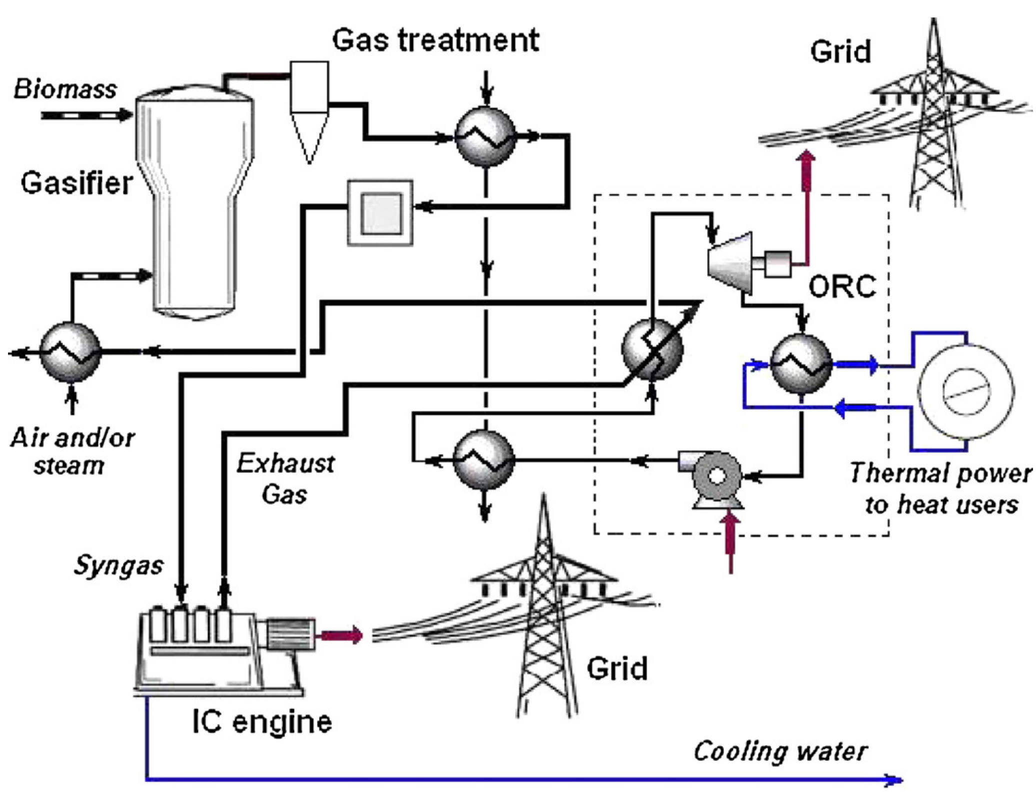


Fig. 9. Cogeneration with gasification and ICE coupled to an ORC from biomass.

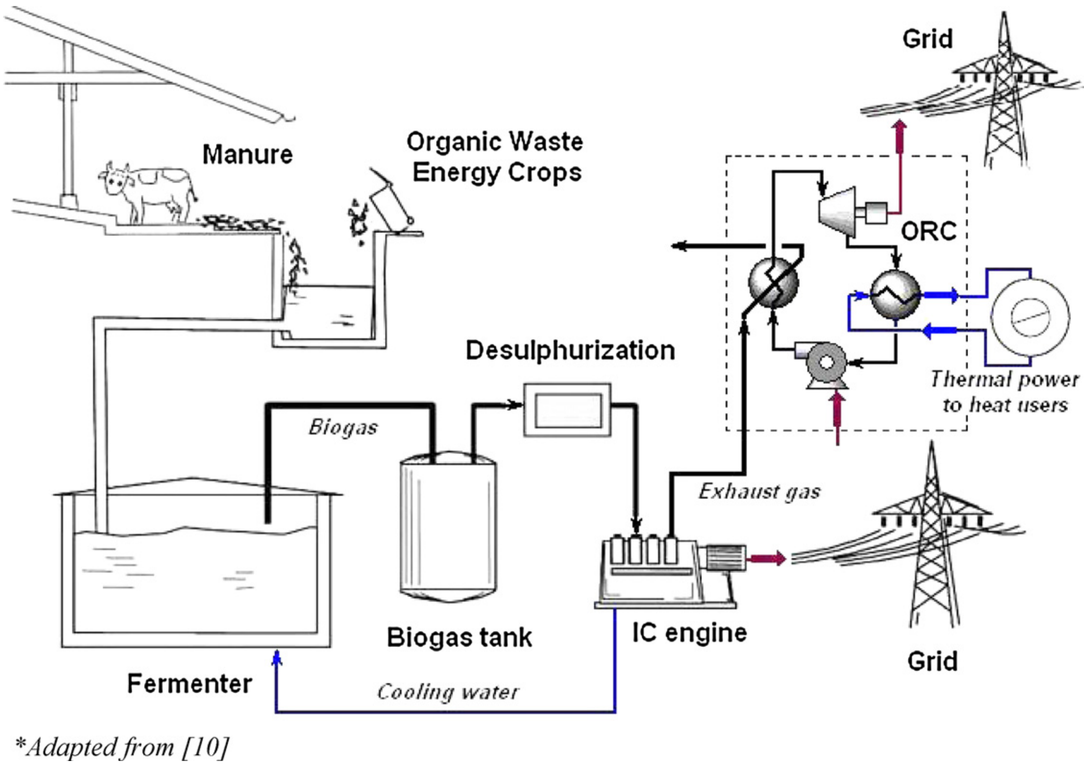


Fig. 10. Cogeneration with biogas and ICE coupled to an ORC from biomass.

investment costs and operation and maintenance are a major 75% and 200% respectively. In addition, there are other parameters in these plants that are difficult to quantify, such as the state of the technology (commercial, pilot or demonstration plants), installation time and cost, the risk associated with performance, reliability, etc. It is worth noting that the ORC has the upper hand in all them. However, even when it is thought that both technologies are competitors as CHP plants, they could also be combined, as shown schematically in Fig. 9, to increase the kWe produced per kilogram of fuel used. This is because, in gasification, the heat to be extracted from the gas cleaning system, as well as the exhausted combustion gas and the cooling water from the Internal Combustion Engine (ICE), could be exploited by its incorporation in an ORC, i.e., a combination of cycles. This system will be dealt with in detail in Section 4.5.3, given that other potential uses of the gas produced by gasifying biomass is combusted in a microturbine or a gas turbine, the exhaust gases could be used to drive an ORC and thus increase the kWe produced as described in Section 4.5.3.

Obviously, with this proposed configuration, the fact of being able to give a use to the residual heat of the ORC condenser (cogenerate) will depend on the flows and temperature ranges achieved in the treatment of the syngas and on the ICE, apart from the thermal needs of the users of that heat.

4.2.3. Biogas

Anaerobic digestion of biomass produces a fuel gas, "biogas", which is introduced to an ICE to produce work. Exhausted combustion gases emerging from this process are used, in part, to maintain a condition of optimum temperature in the digester and the substrate. However, there is a tremendous amount of waste heat that cannot be used sometimes, due to its characteristics and the location of these plants, making this technology currently viable only with subsidies. Therefore, coupling an ORC to produce more electric power by using the waste/rejected heat (as presented schematically in Fig. 10), theoretically reaches a cost of 5.65 c€/kWh, as compared to 13.16 c€/kWh without the ORC [10]. Germany is currently the world leader in the deployment of biogas technology. Its plants produced, in 2008, about 10 TWh electricity per annum, which accounts for about 1.6% of the total demand [42]. Moreover, if we add the fact that in 2007 "alone" a total of 29 TWh of electricity was produced from biogas in the countries belonging to the Organization for Economic Co-operation and Development (OECD) [43]; it can be deduced that the potential of the coupling of both technologies is huge, especially when the trend for biogas is towards more decentralized electricity production in locations with CHP plants [43].

It should be noted that, depending on the temperature levels of the processes, the digester can be heated with the cooling water of the engine, while the ORC is driven by heat from the exhausted gases. However, according to the explanation in [44], the coupling of ORC is currently recommended only for biogas plants with output exceeding 300 kWth and where there is no demand for heat. Similar results were published by [45], where, due to the marginal gain in primary energy input to output ratio, the implementation of an ORC was only recommended for systems that do not include heat applications in the vicinity of a biogas plant. Moreover, as happens when the gasification is connected to an ORC (Section 4.2.2), the fact of giving a use to the waste heat from the condenser (of the latter) depends on the flows and temperature levels reached in the exhaust gases of the ICE, as well as on the thermal needs of the users of that heat.

4.3. Geothermal energy applications

There is an enormous amount of heat available in the world and which represents one of the most important sources of renewable energy. However, the possibility of extracting this energy is subject to a few limited places due to technological and economic reasons [46,47]. For geothermal energy sources with temperatures above 200 °C and producing dry steam or a mixture of steam/brine, the

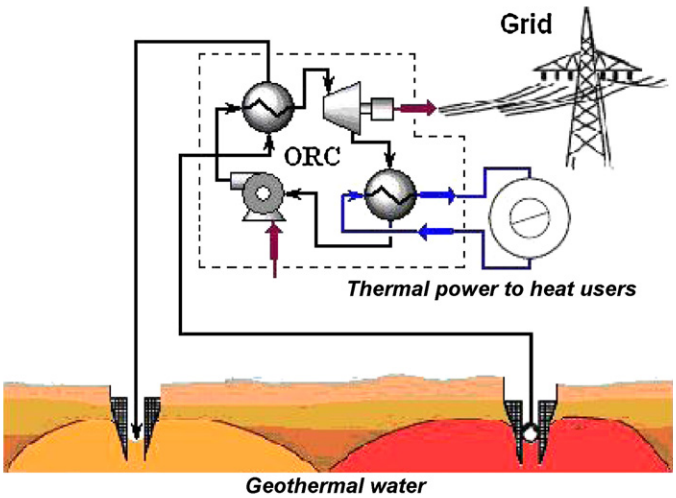


Fig. 11. Typical plant with geothermal generation with ORC.

best method of operation is to use steam directly into turbines in an open cycle with or without reinjection of fluid [48]. For sources with lower temperatures, the use of direct steam is unfeasible and, therefore, an alternative is to produce electrical energy with an ORC as shown in Fig. 11. Here, rather than using it directly, the geothermal fluid transfers its heat to a second fluid that acts as the working fluid of the ORC power plant, thus achieving a benefit from the advantages of these plants, which has already been discussed in this work.

Even with the benefits that this type of facilities supposes, only 32% of installed geothermal plants in the world produce 372 MWe by ORC technology [49]. However, this value only represents 3.8% of the total generated with this type of energy source. An example of a geothermal plant using ORC of 210 kW and water at 98 °C as an energy source is located in Neustadt–Glewe in Germany [10].

Installation costs of these power cycles vary from 1000 to 4000 €/kWe [48,50]. Furthermore, according to research carried out in [51], the cost of geothermal power generation tends to drop significantly; in the year 2005 the cost was between 5 and 15 c€/kWh, and expected to be between 4 and 10 c€/kWh in 2010 and 4 and 8 c€/kWh in 2020. Evidently, there is a wide range of values in generation and investment costs, justified mainly by the different capacities and temperatures found in geothermal heat sources, similar to what happens with the waste heats of processes. This variability requires more research to make this type of plant feasible; for example, in [47], the optimization carried out shows that a regenerated Rankine cycle with a closed type heat exchanger seems the most promising cycle for the exploitation of low temperature liquid-dominated geothermal sources, while in [52,53], it was argued that the ideal cycle is that which uses a working fluid in a supercritical state and regenerative process. In [6], it was found that among the 31 working fluids studied, those that possessed a lower critical temperature obtained the best results when the maximum temperature of the process is 100 °C, while in [50], a methodology was developed to find the optimal point of design of average temperature plants, where basic parameters found were the optimal matching of organic fluids, recovery cycle and the condensation temperature. Other studies that analyzed and compared plants in operation, with low temperature geothermal fluids and ORC's, were carried out in [54], where it is demonstrated that the binary plants can operate with very high exergetic efficiency. Similarly [55], showed how the information provided with an exergetic study can be used for the design, analysis and improvement of the performance. Other techniques for generating energy from low temperature geothermal resources couple the ORC to a VAC (vapor absorption chiller). This achieves a lower condensation temperature, and consequently increases the generation potential. Thus, the whole system can be made viable [56], whereas [57], shows how, by attaching a bottoming ORC to a conventional steam geothermal power plant, the global efficiency of the facility increases by 9%. Likewise, the reviewed literature presents studies of hybrid cycles to raise the efficiency of the facilities, where the geothermal source of low or high temperature is integrated into power plants using fossil fuels, biomass boilers, etc. [46,58] or configurations in series and in parallel, the first being the most efficient working fluids at high critical temperatures, while the second is enhanced with low critical temperatures, according to the results of the ideas discussed in [59].

In summary, ORC plants are nowdays a viable and proven technology for low-enthalpy geothermal sources, with commercial standard modules from 300 to 1200 kW. However, standardized mass production would reduce costs and improve feasibility [20,60].

4.4. Applications with waste heat of processes

Industrial plants continuously waste a large amount of heat energy contained in liquid or gas flows during normal operation [61]. Because this energy loss contributes to an increase in production costs and deterioration of the environment, many efforts have been made during the past two decades to reuse this waste heat. The result has been the discovery of a huge potential for the use and/or recovery of this energy, but the decision to apply heat recovery is basically economic [62]. Industry has many high temperature processes that are also highly inefficient, which would allow the recovery of a large fraction of this energy. However, such a recovery is not practical, due to there being no use for it in the same factory, while the transport to other users is expensive [63,64]. A clear example of inefficient processes occurs in the power generation industry, which has on average a 37% conversion, which means that 63% of the energy input is discarded. Likewise, the cement industry uses approximately 12–15% of the total energy consumed in industries. Using a dry process, the primary energy consumed in a typical cement plant is up to 75% fossil fuel and 25% electrical energy, whereas the pyro-processing requires the major share of the total thermal energy use (93–99%) [65]. Therefore, the recovery of rejected heat and/or exhaust gases of the process can be considered as a potential option to improve energy efficiency in this industry. Similarly, the exhaust gases from a gas turbine normally exceed 500 °C, while the petrochemical industry emits gases at temperatures between 150 and 300 °C. Other examples of industrial processes with large amounts of usable energy, but discarded, occur in the chemical industry, metallurgy, ceramics, etc. [61,66]. As energy costs increase, the harnessing of waste energy in an efficient manner is becoming increasingly more important [67] and therefore, many efforts are aimed at giving a use to this waste heat. One promising technology for the conversion of this heat is the ORC [61–67], whose operating principle has been detailed throughout this paper and works as shown in Fig. 12.

In the literature there are several investigations aimed at finding the technical and economic feasibility of this technology for recovering energy. The authors of [68] show how the irreversibilities that occur in this process depend on the type of heat source, which is how the working fluid p-Xylene develops less irreversibility when high temperature heats are recovered, while the R113 and R123 show a better performance in recovering a low temperature waste heat. This shows the need to find a suitable working fluid for an ORC with waste heat, and therefore, several authors have focused their studies on this issue, for example [61], shows how an ORC using dry fluid hydrocarbons as working fluid, provides better

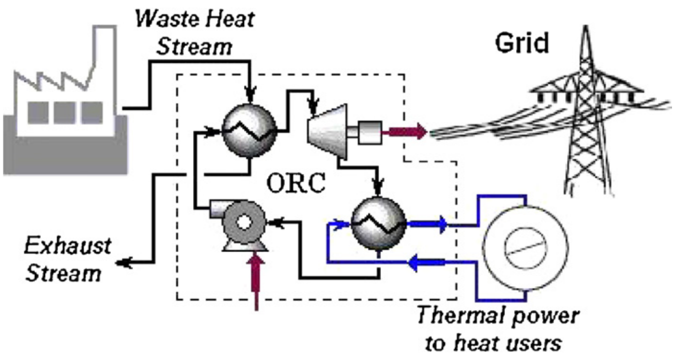


Fig. 12. Typical generation plant using waste heat of the processes with ORC.

benefits in terms of power and efficiency; while [69] found the R123 and R124 to be the most appropriate fluids based on a performance model [70] demonstrated how the efficiency increases as the temperature of waste heat used increases and decreases when using working fluids with low critical temperatures [71] shows how, for the working fluids with a non-positive saturation vapor curve slope, the cycle has the best performance with saturated vapor at the turbine inlet; while a dynamic model that can assume the control strategy of a cycle, of variable heat source and suitable for the simulated operation at partial load or during periods of startup and shutdown, and which aspects cannot be run with a steady model, is carried out in [72]. On the other hand [73], proposed a system that combines low-temperature waste heat and cold energy from Liquefied Natural Gas (LNG). As for the economic analysis, there are several research papers that tackle the issue, for example [74], performed a parametric analysis of an ORC using R113 as working fluid where the high sensitivity of the economic viability of the system to temperatures of condensation, evaporation and overheating can be appreciated; as well as the effectiveness of the regenerator, denoting an optimal combination of these parameters. In the same paper, other essential aspects to be considered in a project with this technology are explained, such as annual operating hours, unit cost of electricity and the cost of manufacturing equipment. Similarly [67], comments that the ORC may be an efficient and cost effective way to convert residual energy into power, and thus, some examples of plants in operation are listed. A unit of 40 kWe ORC, designed for exhaust gases at temperatures between 200 and 250 °C and using tetrachlorethylene as the working fluid, was reported in [75]. The efficiency achieved with this machine was 11%, the estimated cost was 350 €/kWe and the return period was of 3 years when it was used in a tunnel kiln in the ceramics industry. Likewise [36], reported the maintenance costs of an ORC module installed in a cement plant in Germany to be 0.0007 €/kWh. A graph compiled in [67] provides an initial idea of the viability of a project with this type of technology. It relates the temperature of the sources (heat and condensation), with their respective heat fluids, which are presented in Fig. 13.

4.5. Combined cycle applications

Because of the wide range of power of the ORC, it can also recover the waste heat from other power cycles such as turbines and/or microturbines of gas (see Fig. 14), internal combustion engines (Fig. 10), or attached to cooling cycles.

The union of these processes forms combined cycles or "mini-cycles", where the latter, given their small/medium power, are not feasible with conventional technologies, and this increases the interest in the use of ORCs for this type of applications. A review of the status of these technologies is as follows.

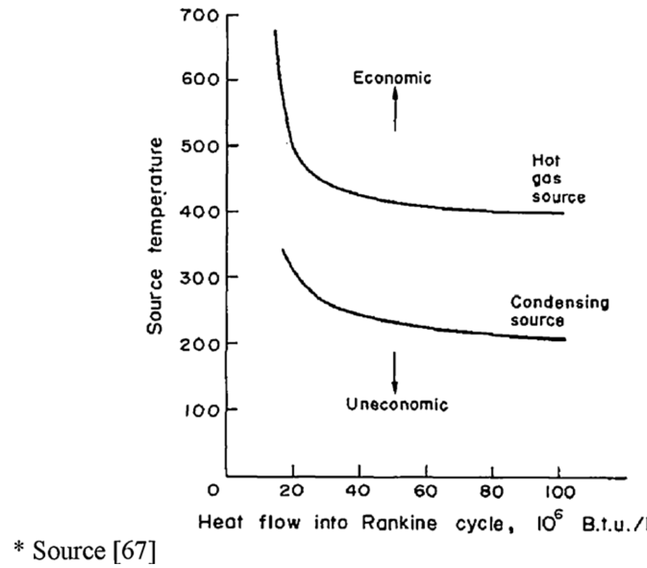


Fig. 13. Economic viability of bottoming type plants.

4.5.1. Gas turbines

Day after day technological advances are obtained, and in this way, for example, the construction of high efficiency gas turbines has been achieved, one of their characteristics is the relatively low temperature of the exhaust gases. Thus, a rigorous analysis has been carried out by [76], where a combined cycle high efficiency gas turbine with conventional Rankine cycle is compared to a new combined cycle high efficiency gas turbine with ORC. The overall efficiency of this new combination increases by up to 3% with respect to the first alternative (depending on the working fluid). However, another interesting conclusion is that similar efficiencies are achieved in both cases (≈60%), but with the difference of requiring lower inlet temperatures to the gas turbine for the second option, also obtaining a reduction of NOx and construction and maintenance costs. Also [76], shows how these new combined cycles are economically attractive when the cost of the gas turbine and the ORC are less than 350 €/kW and 2000 €/kW, respectively. A similar comparative study for the use of combustion gases from gas turbines, which are currently being used in compressor

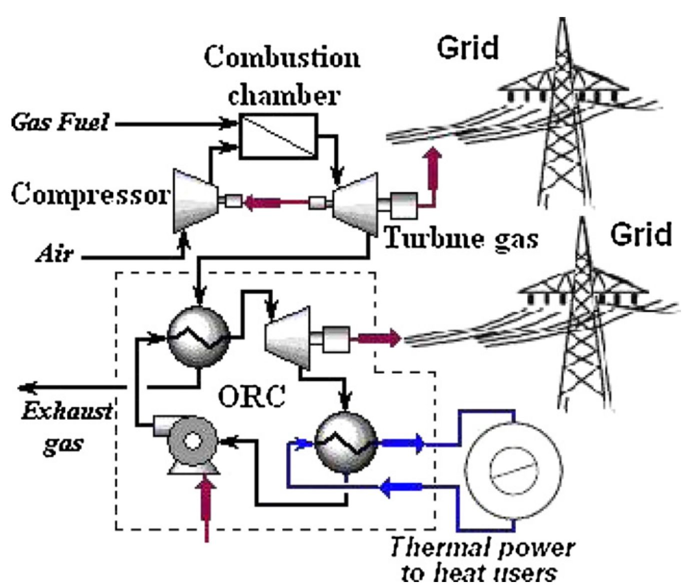


Fig. 14. Combined cycle turbine/microturbine of gas – ORC.

stations for natural gas in Spain, was reported in [77]. The authors recommended the ORC technology for the production of 5 MWe as a bottoming cycle, due to its high reliability, low need of personnel, good performance at partial loads that will be submitted (due to the modulation of compressor stations) and lower investment cost (1500 €/kW for the ORC, compared to 2050 €/kW for the steam cycle). On the other hand [78], reported the use of cryogenic energy contained in the LNG. With this aim, these researchers propose a cascading power cycle consisting of a Rankine cycle using ammonia–water as the working fluid, Brayton power cycle with combustion gas and an open LNG cycle. Their results show the economic benefits this process brings, due to the increase of the work generated by the expansion of the LNG and the reduction of work consumed by the compressor and pump of the Brayton and Rankine cycle respectively.

4.5.2. Gas microturbines

A study to analyze the feasibility potential of combining gas microturbines with micro-ORC was conducted by [79]. These authors show that, for a 100 kWe microturbine, it is possible to obtain an additional 45 kW of electricity using residual heat by means of a micro-ORC and thereby move from an electrical efficiency of 30% to 40%. In addition, output gases of the ORC can get 30 kW of low temperature (≈100 °C) for cogeneration purposes. However, these combined minicycles are particularly suitable for plants where cogeneration (the heat) has little importance as compared to the production of electricity. The estimated cost for the entire system, according to these authors, is about 4000 €/kWe [79]. The analysis after combining gas microturbines and ORC has been done by other researchers [80,81], who report periods of return on investment of less than 3 years for the complete system.

4.5.3. Internal combustion engines

As mentioned at the beginning of this section and as shown in Fig. 10, the ORC can also recover the waste heat from combustion gases and/or from cooling systems of the ICE. In this way, it can form combined cycles, or combined "minicycles", that obviously depend on the power of ICE. Several investigations aimed to analyzing the behavior of such processes have been reported in [82,83], among others. A study that examines the potential for the recovery of waste heat from a dual-fuel, high efficiency, low emissions and low temperature exhaust gases ICE coupled to the ORC is carried out in [84]. With this system, an improvement of 7% in the efficiency of the fuel conversion and a decrease of 18% in specific NOx and CO_2 emissions was obtained. This same paper presents a brief summary of several studies that discuss the issue of heat recovery with ORC, from the theoretical, simulation, review and experimental points of view. The authors of [83] analized the recovery of energy contained in the combustion gases of an ICE under three different configurations; a simple cycle using only exhausted gases, a simple cycle recovering exhausted gases and cooling water of the engine and finally, a regenerative cycle. This analysis shows an increase of up to 12% in the overall efficiency with respect to the cycle without any type of recovery. In addition, they also noted the small amount of energy that can be recovered from the cooling system of the engine. The highest values (which are very similar) of efficiency of the combined cycle are given for the cases where the ORC is preheated and regenerative ($\eta_{cc} \approx 47\%$).

A thermoeconomic comparison of different configurations and combined cycles (gas turbine – ORC and gas engine – ORC), involved in the process of the vaporization of natural gas, has been carried out by researchers [85]. The results of this research show the greatest efficiency for combined cycles with gas engine, with either one or two ORCs (51.7% and 54.2%, respectively). However, the specific cost of the plant is higher (1296 and 1475 €/kW) for these configurations, when compared with the proposed combined cycle with gas turbine – ORC, whose cost is 1028 €/kW.

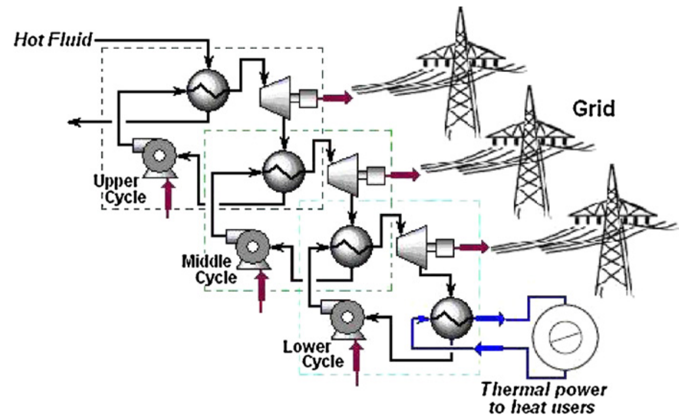


Fig. 15. Rankine cycles in cascade.

Investigations carried out to study the feasibility of combined cycles of ORC coupled to diesel engines have been reported in works such as [82,86]. The recovery of heat contained in exhaust gases from two diesel engines, of 8.9 MWe each, has been analyzed in [82]. The authors compare two technologies for this recovery, ORC and Kalina cycle and, although the net power obtained after the recovery is fairly similar (1603 and 1615 kW, respectively), to obtain a maximum performance, the Kalina cycle requires pressures of operation up to 100 bar, while the ORC only requires about 10 bar. Therefore, the adoption of the Kalina cycle is not interesting for this type of applications, due to its low benefits. Additionally, it would require a plant resistant to high pressures and with a greater degree of complexity. A small pilot plant (10–25 kWe) was realized in [86] to integrate solar energy with a combined cycle of a biodiesel engine with two ORCs in cascade (see Section 4.6), achieving overall efficiencies of 41%.

Even when, in the systems discussed below, the waste heat from one of the cycles is not used by the other, as occurs with the combined cycle described before, it is true that there is a co-existence of two thermodynamic cycles in the same system, since the ORC is used to recover waste heat from other processes and hence, the work produced by this directly activates the other cycle. For example:

4.5.4. Vapor compression

The production of cold by the coupling of a vapor compression cycle and an ORC was evaluated and its feasibility demonstrated through a lab scale prototype, which was designed according to the model developed in the same paper [87]. In the system designed for 5.3 kW, the ORC activates the compressor of the refrigeration cycle by compression. However, the prototype built showed a slightly lower cooling capacity, ranging between 3.5 and 4.5 kW.

4.5.5. Heat pump

The coupling of a heat pump with an ORC is another form of cooling in which, similarly, the ORC acts by contributing to the mechanical work for the compressor of the heat pump [67].

4.6. Cascade applications

Additionally, and again thanks to its large power ranges and the diversity of temperatures from the heat source, it is possible to couple an ORC either to a conventional Rankine cycle or to another ORC, where the condenser of one acts as an evaporator of the next and so on, in a cascade, as shown in Fig. 15.

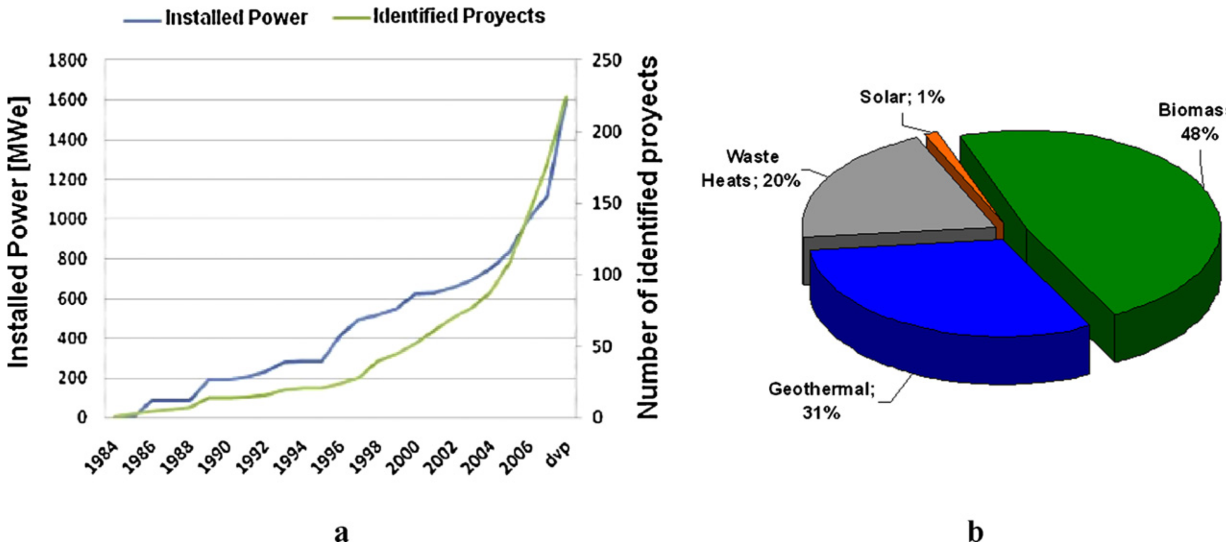


Fig. 16. Evolution (a) and distribution of application (b) of the ORC technology.

An example of these Rankine cycles in cascade is carried out in [57]. These researchers propose to send a certain amount of steam from the turbine to a Rankine cycle of conventional steam that operates as a heat source for an ORC. This, in turn, is coupled to another ORC, in which the first condenser acts as an evaporator for the second. The results of this study show an increase of 9% in the overall efficiency of the proposed plant.

On the other hand, a thermodynamic analysis of multiple cycles of ORCs, with a single working fluid (R113), has been carried out by [88]. The system produces steam at various pressures and uses 4 evaporators with temperature drops of 120/100, 100/80, 80/60 and 60/40 °C, achieving in this way a production of 12.4 kWe, assuming 100 kW of heat recovered from the source of residual heat. Other works done, in [30,31,89] among others, which take solar radiation as the energy source, analyze the use of a double cascade ORC for the production of fresh water through reverse osmosis. In [30] for example, how the analyzed system can be competitive with conventional desalination processes is presented. The main findings, already illustrated in Section 4.1.2 of this paper, refer to the area of solar field required per m^3 of water, which is much lower than with traditional solar distillation process. Similarly, reviewing Section 4.1.2 of this paper, the research of [31] was mentioned, which has a configuration similar to the previous one, but with other working fluids (for lower temperatures). The specific cost of fresh water was calculated in about 6 €/m^3. A cost close to the previous was found in [89] for the cascade system. This paper presents a rigorous economic evaluation, in which four processes are analyzed for producing fresh water by solar radiation and reverse osmosis, a photovoltaic system (with and without batteries), a low temperature ORC and two ORCs coupled in cascade. The latter has a cost of 6.85 €/m^3, significantly similar to those found for systems with photovoltaic panels, thus becoming a competitive alternative both economically and technologically.

4.7. Fuel cells

Few studies that examine the results that can be achieved by coupling the ORC to a fuel cell have been reported. However, the authors of [90,91] present a theoretical study for trigeneration plants, where waste heat rejected in a fuel cell SOFT is used to heat the organic fluid of the ORC. On the other hand, the waste heat of the ORC is used for heating and/or cooling (the latter through an absorption chiller of simple effect). The results from these studies show that the efficiency of the trigeneration plant is 74% (with a maximum net work produced of 540 kWe), while, if it only had the plant in cogeneration mode for heating aims, the efficiency would be 71%, cogeneration with cooling purposes woud be 57% and for electricity generation by power cycle alone (SOFC and ORC) would be 46% [90]. Likewise [91], shows how, as the density of the current of the SOFC increases, the exergetic efficiency for the power cycle as well as cogeneration for cooling and heating, and even for whole trigeneration plant, decreases.

5. Manufactures and evolution of the ORC market

As it can be seen from Section 4, the technology associated with ORC was, until recently, still under investigation. However, demonstration and commercial plants have recently been developed what have made that this technology is growing rapidly. Fig. 16a shows the evolution of the MWe and the number of plants installed up to 2006, according to a study carried out by [92]; while Fig. 16b shows the distribution by type of application [93]. The market for this technology has experienced such a strong growth in the last 4–5 years that one single company [18], up to June 2011, had installed almost the same number of plants as all projects identified in 2006 by [92].

From Fig. 16, we can see that the ORC is a mature technology for applications with waste heat recovery, biomass and geothermal sources. However, this is still incipient for applications with a solar energy source. Furthermore, as shown in Table 1, this technology is quite well developed for the MW power range, there being very few ORC plants available in the kW power range, according to the review of the main manufacturers that produce the ORC technology worldwide, presented in this same Table 1.

6. Economic analysis

Because of the lack of any real installations to show the cost of this type of machines, a simple economic analysis has been carried out to find the maximum investment that a project can assume when the return on investment is required in a year. The methodology developed consists of calculating the kWh that 10 kW (for households) and 100 kW (for the industry) ORC machines can produce, working 8000 h per year and whose fuel cost is none. These kWh produced mean a maximum saving (in monetary terms) of not having to buy that amount of energy. However, considering a 10% of fixed operation costs, the maximum reasonable investment

Table 1
Main ORC manufacturers of ORC modules worldwide.

Company/Country	Application	Range of power (MW)	Heat source temperature (°C)	Technological aspects	Reference
Turboden/Italy	1, 2, 3, 4	0.4–2.2	>250	WF: OMTS, Solkatherm Efficiency: 17–23%	[18]
Ormat/United States	2, 3, 4 5→	0.20–22 2×10^{-4}–4×10^{-3}	150–300	WF: n-pentane	[20]
Pratt & Whitney Power Systems/United States	1, 2, 3, 4	0.22–0.26	91–149	WF: R245fa	[94]
FREEPOWER/England	1, 2, 3, 4	0.12	>110	T: High speed	[95]
Infinity Turbine/United States	3, 4	0.01–0.05→ 0.25→	<90→ 90–120→	WF: R134a WF: R245fa	[96]
Maxxtec-Adoratec/Germany	1, 3, 4	0.3–1.6	>300	WF: OMTS	[97]
Barber Nichols/United States	3, 4	0.7, 2.0, 2.7	>115		[98]
GMK/Germany	1, 3, 4	0.5, 2.0	>100	WF: GL-160® WF: WL-220®	[99]
LTi REEnergy/Germany	4	0.03	>160		[100]
TRI-O-GEN/Nederland	4	0.06, 0.16	>350	WF: Toluene T: Turbo-expander	[101]
Eneftech/Switzerland	1, 2, 3, 4	0.005, 0.010→ 0.020, 0.030→	>120 <200	T: Scroll	[102]
Electratherm/United States	1, 2, 3, 4	0.03–0.05	>88	WF: R245fa T: Twin Screw Expander	[103]
GE Power & Water/United States	1, 2, 4	0.12	>115 <240	WF: R245fa T: Single state radial flow	[104]
TransPacific Energy/United States	2, 3, 4	0.10–5.0	>30 <480	WF: TPE®	[105]

1, Biomass; 2, solar; 3, geothermal; 4, recovery of heat; 5, remote units. WF, working fluid; T, type of turbine.

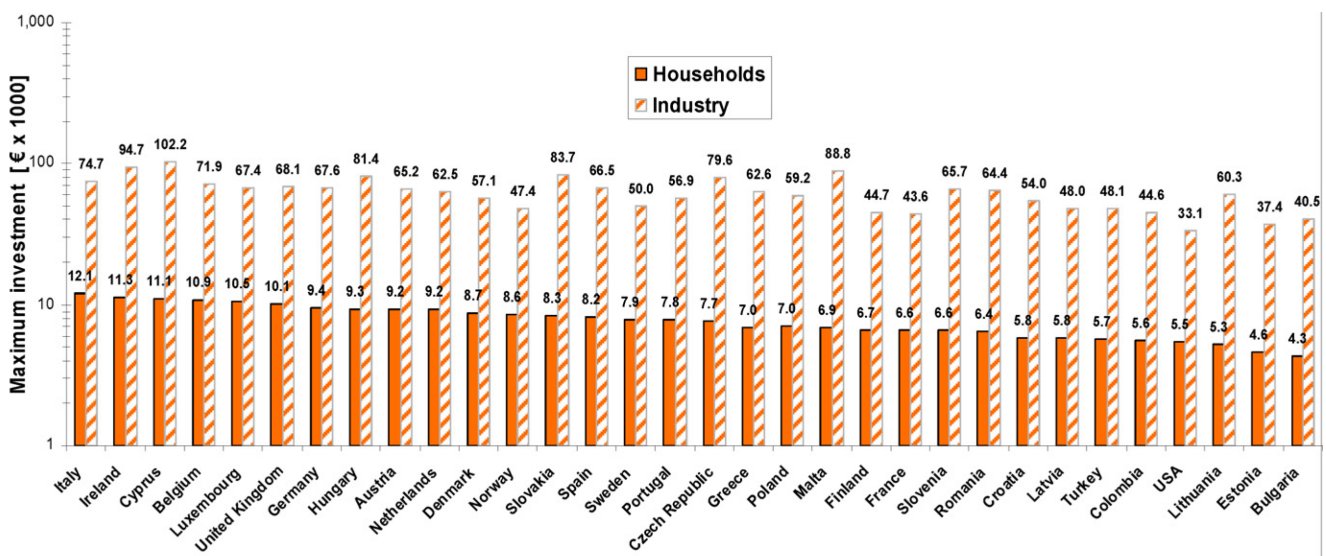


Fig. 17. Maximum investment (in the logarithm scale) at industrial and household level for the countries under study.

assumed could be 90% of this saving. Table 2 shows the kWh price in 2008, for industry as well as for households in various countries (some EU countries, the USA and Colombia), which is the aim of the present study.

Fig. 17 presents the results on semi-log scale of the previous economic analysis, which would serve as a first and basic study of a project with ORC technology to be implemented in one of the countries under study. Evidently, where the cost per kWh was higher, a higher cost of the project can be assumed in both sectors. For example, for the case of the USA and Colombia, the cost of the project at residential level is practically equal, whereas for the industrial sector, a notable difference is detected.

Table 2
Cost of the kWh in industry and households in the selected countries.

Country	€/kWh		Reference
	Households	Industry	
European Union	[a]	[a]	[106]
USA	0.0750	0.0455	[107]
Colombia	0.0766	0.0613	[108]

[a] Variations according to the country as mentioned in [99].

7. Conclusions

Based on the technical review conducted in this work, it can be stated that the ORC technology, acting as “topping” or “bottoming” cycle, has an enormous potential, from the technical and economical point of view, for the production of heat (for heating, domestic hot water, drying processes in industry, absorption cooling, etc.) and/or for mechanical and electrical energy (from a few kWe to some MWe) from renewable energy sources such

as biomass, solar and geothermal and waste heat from industrial processes or other technologies, making them ideal for the energy self-sufficiency of small populations and industries. This will result in a continuous increase in the number of companies devoted to this emerging subject (for implementation, as well as for manufacturing and distribution), since the lack of low values in fuel costs, in a certain sense, corrects the relatively low electrical efficiency of these devices. In addition, it is worth emphasizing the fact that, up to now, there has been no single fluid that satisfies all aspects that have to be considered in a real ORC cycle; whereas plants of only a few kWe are subject to the inclusion of the appropriate equipment for a strong start-up of a business.

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